

# Looking Ahead

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## Background

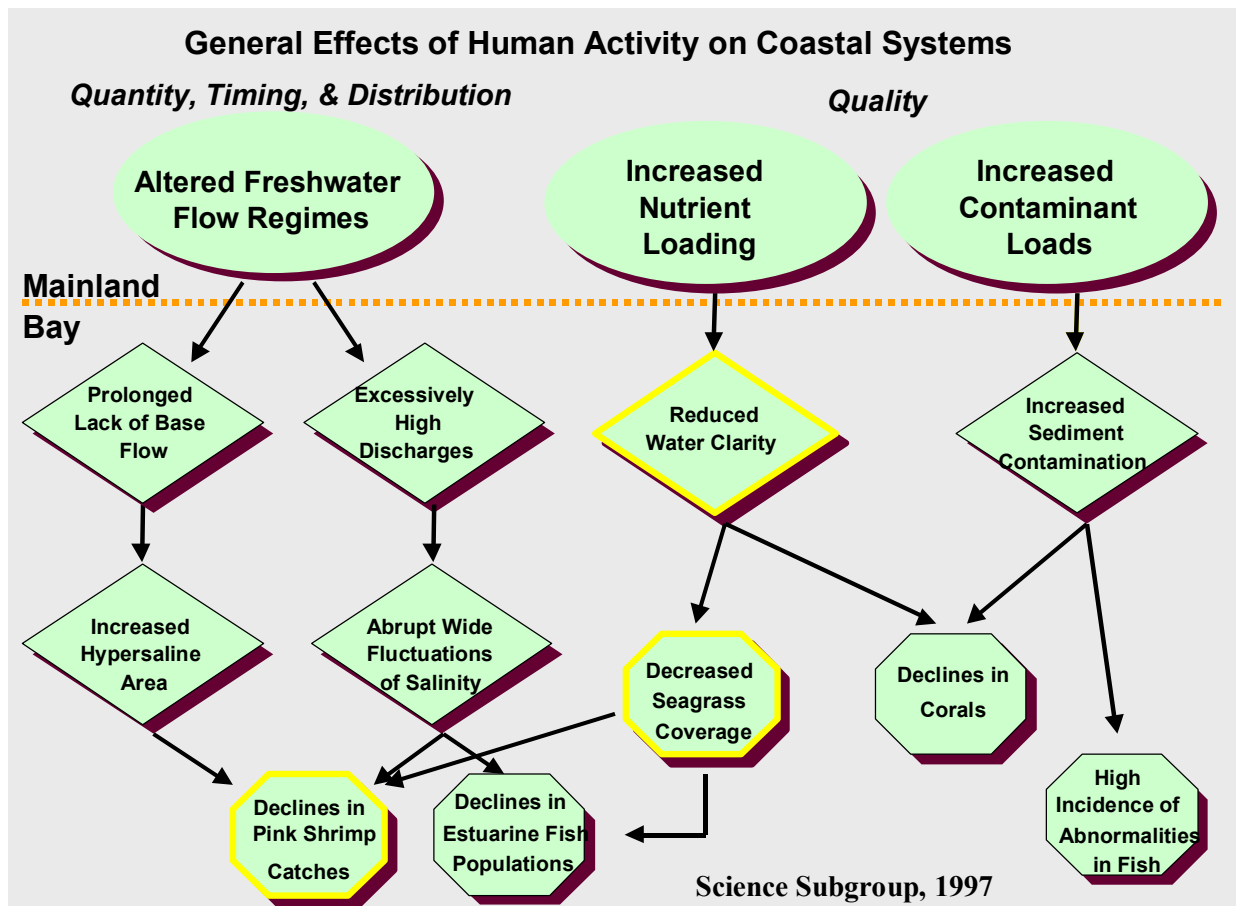
Since 1994, the Florida Bay Science Program has coordinated a program of ecosystem research designed to shed light on the causes of ecological changes that occurred in Florida Bay during the late 1980s and early 1990s, most visibly seagrass dieoff and algal blooms. These changes, believed at the time to be chiefly precipitated by human forces, were hypothesized to have altered historical patterns of circulation, water quality and biotic communities in the Bay. The main goal of the Program has been to understand the major driving processes and their interactions that were responsible for these changes in the Bay, both those that can be modified by human actions such as the flows of fresh water into the Bay, and those solely to forces beyond management control such as storms and sea level rise. This focus is reflected in the five strategic questions that organize the research. The more general objectives of the Florida Bay Science Program have been to develop this knowledge and combine it with data on biological responses to help define restoration goals, to predict system response to management actions, and to establish success criteria.

Adoption of the Comprehensive Everglades Restoration Plan in 2000 establishes ecosystem restoration as the organizing principle for the management of natural resources in South Florida. In many ways the objectives and ideas employed by the cooperating agencies to establish the Florida Bay Science Program have now been adopted as the general basis for interagency cooperation throughout the region. However, CERP represents a fundamental change in natural resource management within which the Florida Bay Science must now function and deliver results. Adoption of CERP refocuses attention of managers on future ecological benefits to be achieved through restoration, and it establishes new mechanisms for regional interagency planning and coordination. These changes warrant a review of progress by the interagency Florida Bay Science Program toward specific goals for research and an evaluation of the Program's approach to pursuing its general objectives.

## ***Information Needs***

The 1997 report of the Science Subgroup (Science Subgroup 1997) captures the consensus of that time about how changes in quality, quantity, distribution and timing of freshwater flows affect estuarine and marine waters. The conceptual model shown in Figure 9.1 summarizes the hypothesized causal relationships linking these to changes recently observed in Florida Bay. Ecosystem research provides information needed by resource managers in three areas: 1) confirm those linkages that are not understood fully; 2) investigate and describe unrecognized links; and 3) construct quantitative models managers require for detailed planning and assessment of restoration projects.

**Figure 9.1: General conceptual model linking quantity, quality, timing and distribution of freshwater flows to observed changes in estuarine and marine systems (Science Subgroup 1997). Yellow outlines highlight changes in Florida Bay that were observed in the late 1980s and early 1990s. Connections in the model diagram represent hypothesized causal links to the environmental effects of human activities, at the top of the diagram, and to consequences elsewhere in the ecosystem, lower in the diagram.**



In response to this need, the Florida Bay Science Program formulated a plan to develop and implement a research strategy designed to merge scientific understanding of the Bay with management's decision-making process (PMC 1997). Five central questions coordinate ecosystem research (see box). These questions have continued until the present as the focus of research. The strategic plan establishes the following additional principal functions for the Program and describes activities to support these functions:

- facilitate a consensus-based process for determining science needs and priorities,
- promote funding of critical science needs,
- develop and maintain an open and scientifically sound review process for evaluating research results and for advancing the research program, and
- communicate research results and program progress to the management and scientific community.

**Question 1 - Physical Processes:** How and at what rates do storms, changing freshwater flows, sea level rise, and local evaporation/precipitation influence circulation and salinity patterns within Florida Bay and outflows from the Bay to adjacent waters?

**Question 2 - Nutrient Dynamics:** What is the relative importance of the influx of external nutrients and of internal nutrient cycling in determining the nutrient budget for Florida Bay? What mechanisms control the sources and sinks of the Bay's nutrients?

**Question 3 - Plankton Blooms:** What regulates the onset, persistence and fate of planktonic algal blooms in Florida Bay?

**Question 4 - Seagrass Ecology:** What are the causes and mechanisms for the observed changes in seagrass community of Florida Bay? What is the effect of changing salinity, light and nutrient regimes on these communities?

**Question 5 - Higher Trophic Levels:** What is the relationship between environmental and habitat change and the recruitment, growth, and survivorship of animals in Florida Bay?

The strategic plan envisions that various modeling activities will integrate results across the Program and deliver these to resource managers. Conceptual models will synthesize our understanding of Florida Bay and help formulate critical hypotheses about the Bay's response to upstream hydrology, water quality or other restoration actions. Model will identify information needs and assist in prioritizing those needs and identifying research tasks. Ultimately, numerical models used in a predictive mode will link research understanding of the Florida Bay ecosystem to environmental management decisions by predicting the likely outcomes of various management alternatives on the Bay. These predictions then become hypotheses about the results of management actions, which will be testable by observation through monitoring.

### ***Ecosystem Perspective***

Resource managers need to understand the whole of the Florida Bay ecosystem and its relationship to other ecosystems in South Florida. In general, the characteristics of an ecosystem reflect the influence of its regional geomorphic setting, hydrology, oceanography, and climate, and the dynamic response of physical and biotic components within the ecosystem to these large-scale driving processes. Geomorphic setting, the underlying geology and associated geochemistry, serves as the template on which the ecosystem develops. Climate and associated

environmental processes, especially the water cycle, drive ecological processes and thus influence the structure and function of the ecosystem. Singular events, such as large storms, flood, fire, etc. can cause rapid change or disturbance, and characteristics of the ecosystem might be defined by the gradual recovery from these events, i.e. through succession. Human activities influence ecosystem structure and function both directly and indirectly by altering the processes that drive ecosystem functioning and by altering the geomorphic setting.

Each of the five central questions examine different characteristics of Florida Bay and the relation of these to particular driving processes and attributes of the geomorphic setting, Table 9.1. Similar tables in the preceding chapters link specific results of the research program with the ecosystem characteristics and functional relationships addressed by each central question. Individual research projects inevitably must focus on component parts and processes within the ecosystem and the interrelationships between Florida Bay and adjacent ecosystems. The five central questions distribute the research effort across the elements of the ecosystem so that results of individual projects provide the breadth of information needed to characterize the entire ecosystem.

Questions 1 and 2 investigate the response of the physical and biogeochemical characteristics of Florida Bay to variations in external, driving processes. Question 2 also seeks to understand the influence of nutrient fluxes across the boundaries of the Bay relative to processes that cycle and redistribute nutrients within the ecosystem.

Questions 3 and 4 investigate the variation in particular characteristics of the ecosystem, i.e. plankton concentrations in the water column and the distribution and composition of benthic communities. In contrast to the first two questions, which can draw on principles of physics and chemistry to a large degree, Questions 3 and 4 present researchers with challenge to uncover the unknown mechanisms and related principles that govern the variation in plankton concentrations and seagrass communities.

Finally, Question 5 investigates how higher trophic level species respond to changes in ecosystem characteristic that subject of investigation under the other central questions.

**Table 9.1: Topics of ecosystem research in Florida Bay related to each strategic question**

	<b>Driving Processes</b>	<b>Ecosystem Characteristics</b>	<b>Geomorphic Setting</b>
<b>Question 1</b>	<ul style="list-style-type: none"> <li>• Storms and wind</li> <li>• Changing freshwater inflow</li> <li>• Sea level and tides</li> <li>• Patterns of evaporation and rainfall</li> </ul>	<ul style="list-style-type: none"> <li>• Circulation pattern</li> <li>• Salinity pattern</li> <li>• Outflows to adjacent systems</li> <li>• Bathymetry</li> </ul>	<ul style="list-style-type: none"> <li>• Connectivity to reef tract and Florida Shelf</li> </ul>
<b>Question 2</b>	Nutrient loading from: <ul style="list-style-type: none"> <li>• Everglades runoff</li> <li>• Atmosphere</li> <li>• Keys wastewater</li> <li>• Groundwater</li> <li>• Adjacent coastal waters</li> </ul>	<ul style="list-style-type: none"> <li>• Water quality and sediment geochemistry</li> <li>• Internal nutrient cycling, water column/benthic nutrient exchanges</li> <li>• Nitrogen fixation</li> </ul>	<ul style="list-style-type: none"> <li>• Regional geologic sources and sinks for nutrients</li> </ul>
<b>Question 3</b>	<ul style="list-style-type: none"> <li>• Changes in nutrient loading</li> <li>• Factors affecting water residence time in the Bay</li> <li>• Factors affecting sedimentation and resuspension rates</li> <li>• Blooms on the Florida Shelf</li> </ul>	<ul style="list-style-type: none"> <li>• Internal factors driving changes in growth rates, grazing and physical losses</li> <li>• Planktonic algal blooms</li> </ul>	<ul style="list-style-type: none"> <li>• Factors affecting physical losses of plankton from the Bay</li> </ul>
<b>Question 4</b>	<ul style="list-style-type: none"> <li>• Climate, storms</li> <li>• Fresh water flow</li> <li>• Disease</li> </ul>	<ul style="list-style-type: none"> <li>• Seagrass and hardbottom communities</li> <li>• Temperature and salinity</li> <li>• Light attenuation</li> <li>• Sediment texture</li> </ul>	<ul style="list-style-type: none"> <li>• Sediment geochemistry</li> </ul>
<b>Question 5</b>	<ul style="list-style-type: none"> <li>• Factors driving change in salinity, water quality, and benthic habitat)</li> <li>• Factors affecting movement between adjacent systems</li> <li>• Fishing</li> </ul>	<ul style="list-style-type: none"> <li>• Habitat (salinity, water quality, benthic habitat)</li> <li>• Higher trophic level species</li> </ul>	<ul style="list-style-type: none"> <li>• Factors affecting movement between adjacent systems</li> </ul>

## Status of Research Program

This section evaluates the degree to which the Florida Bay Science Program has addressed each of the five central questions and reviews areas of ongoing research interest identified in the preceding chapters. The evaluation is based on information in three areas: 1) coverage of the topic area, 2) the degree of synthesis achieved on the topic, and 3) progress on development and verification of predictive models. Coverage of the topic area is judged primarily based on the summary tables developed for each question that associate individual results, i.e. citations to journal publications, abstracts, etc., with the components of the ecosystem, their response to driving factors and interactions with each other, i.e. Table 9.1. The degree of synthesis achieved is evaluated based on the hierarchy of “regional information synthesis” described in NRC (2003, page 69; below), i.e. description, correlation, mechanistic models, and hybrid simulation models. Model development generally parallels the degree of synthesis, reflecting the integrative and synthetic role of modeling. Evaluation draws on the information on the state of model development on each central question that is included as part of the preceding chapters.

“Several synthesis approaches that have been used to examine ecosystems in the past are applicable to the South Florida ecosystem. These include synthesis of descriptive data, correlations of ecological data with changes in environmental conditions, mechanistic models to make large-scale predictions, and a combination of these methods (Hobbie, 2000). Synthesis of descriptive data, the simplest form of synthesis, might involve descriptions of changes in the characteristics of ecosystems (e.g. organic matter accumulation) and in physical factors (e.g. hydroperiod) over time. Statistical correlations between biological responses and environmental factors may take the form of periphyton response to phosphorous loading. [...] Mechanistic simulation models could be used to predict a single process (e.g., rate of mercury methylation) or interrelated processes (e.g. wading bird nesting coupled with a hydrological model). Sophisticated models that combine simulation modeling with descriptive and correlative methods are also possible – e.g., the Everglades Landscape Model ([www.sfwmd.gov/org/wrp/elm/](http://www.sfwmd.gov/org/wrp/elm/)), which combines hydrodynamics, nutrient transformations, and translocation with plant production and community composition responses. Each of these approaches offers opportunities to enhance our understanding of the complex interactions of the physical, chemical, and biological factors that characterize the greater Everglades ecosystem, ultimately facilitating factors South Florida restoration activities by reducing uncertainties about overall ecosystem response.”

- quoted from Box 5-2, Tools for Learning; NRC 2003

**Question 1 - Physical Processes**

*How and at what rates do storms, changing freshwater flows, sea level rise, and local evaporation/precipitation influence circulation and salinity patterns within Florida Bay and outflows from the Bay to adjacent waters?*

**Coverage of topic**

Research and monitoring of physical processes covers the driving processes (i.e. winds and storms, precipitation, evaporation, surface water inflow, groundwater, sea level and tides, and boundary currents) and characteristics of the ecosystem (i.e. salinity patterns, circulation patterns, and exchanges with adjacent waters). Some data exist on each of the driving processes and ecosystem characteristics. More work remains to fully characterize groundwater and evaporation. For both, the available flux estimates vary over a significant range of values. In the case of groundwater, a mechanistic model has yet to emerge that can explain the magnitude of groundwater discharge to the Bay that has been reported in the peer-reviewed literature. Elsewhere, basic measurements of bathymetry, depth, and flow still have yet to be done across the extensive mud banks that divide the inner portion of Florida Bay.

Work remains to analyze the sensitivity of ecosystem characteristics to the different forcing factors. On going observations and monitoring aimed at constructing water and salt budgets for the Central region will address this deficiency, but results are still preliminary. Meanwhile, little attention has been paid to investigating the influence of sea level fluctuations on circulation patterns and residence time in the inner portion of Florida Bay. Sea level fluctuates about 20 cm within a normal year. This represents a substantial change in the depth of the water column for shallow portions of the Bay, such as the Central region, and thus it can be expected to affect circulation and flushing.



**Level of synthesis**

<b>Description</b>	<p><b>Salinity</b> – paleoecological data and historical data have been compiled and analyzed for trends in salinity and variation in salinity</p> <p><b>Circulation and Exchange</b> – ongoing monitoring on shelf region west of Florida Bay with current meters and drifters, sporadic data exist for currents in passes between Keys and deeper cuts within Florida Bay</p> <p><b>Driving processes</b> – monitoring data on all except groundwater discharge and evaporation</p> <p><b>Bathymetry</b> – lacking information on elevation (depth) of bank tops</p>
<b>Correlation</b>	<p><b>Coastal oceanography</b> – correlation of current patterns with seasonal winds</p> <p><b>Salinity</b> – regression and time series models link salinity with characteristics of Everglades hydrology on both long-term (paleoecological data) and short-term.</p> <p><b>Sea level</b> – remains to be investigated, other combinations of driving processes and ecosystem characteristics are thought to not be significant based on physical reasoning.</p>
<b>Mechanistic models</b>	<p><b>Salinity</b> – mass balance models link salinity variation with net freshwater supply, including effects of runoff and evaporation – but not groundwater. Understanding of the physical mechanisms that might support measured groundwater discharge rates is lacking.</p> <p><b>Circulation and exchange</b> – confident that physical mechanisms operating in other estuaries apply to Florida Bay, but there is not a generally accepted implementation of a hydrodynamic model for the Bay.</p> <p><b>Groundwater</b> – lacking an understanding of the physical mechanisms driving groundwater discharge into Bay except in case where differences in head between the Bay and the Atlantic drive flow under the Keys.</p>
<b>Simulation models</b>	(none)

## Question 2 - Nutrient Dynamics

*What is the relative importance of the influx of external nutrients and of internal nutrient cycling in determining the nutrient budget for Florida Bay? What mechanisms control the sources and sinks of the Bay's nutrients?*

### Coverage of topic

Some information has been developed on each the major components of the nitrogen and phosphorous budgets of the inner portion of Florida Bay. This provides a context for judging the influence of some nutrient sources that have been seen as threatening the health of the Bay, such as wastewater discharges from the Keys. However, uncertainty in estimates of the larger fluxes and lack on information on their temporal variation hampers our understanding of the significance and possible role of other nutrient sources, such as in surface water discharge from the Everglades and in groundwater. Information on internal nutrient cycling has not yet been integrated with information on the Bay's nutrient budget. The influence of seagrass community (composition and density) and higher trophic level species (e.g. sponges) on nutrient fluxes and internal cycling has not been determined.

### Level of synthesis

<b>Description</b>	<p><b>Water quality</b> – extensive water quality monitoring data exist, and these have been analyzed to describe temporal trends and “zones of similar influence.” There is some paleoecological data indicating a trend of increasing nutrients in the Bay since about 1980.</p> <p><b>Nutrient cycles</b> – work is still underway to describe major pathways, fluxes, rates of transformation and associated nutrient species in Florida Bay and in the adjacent mangrove wetlands.</p>
<b>Correlation</b>	<p><b>Everglades runoff</b> – analysis of nutrient concentration/loading as a function of freshwater discharge has been done as part of work to investigate metabolism of coastal mangroves.</p> <p><b>Eutrophication</b> – one hypothesis to explain plankton blooms invokes increased nutrient loading with increased inflow of freshwater through the 1980s and 1990s. This is supported by correlative arguments, but these correlations have yet to be tested rigorously.</p>
<b>Mechanistic models</b>	Mechanistic models of nutrient cycles are being formulated and investigated as part of the FCLTER research. Beyond this, little has been done to formulate and test mechanistic models that might be able to explain the variation in water quality documented in the monitoring data.
<b>Simulation models</b>	Preliminary work has been done to adapt and calibrate a water quality model that supports simulation of plankton blooms and seagrass (Cerco 2000). Lacking supporting information from a coupled hydrodynamic model, this model cannot be fully calibrated and verified.

**Question 3 - Plankton Blooms***What regulates the onset, persistence and fate of planktonic algal blooms in Florida Bay?***Coverage of topic**

Much of the work in this area has focused on the various effects of nutrients either as the trigger for blooms or on nutrient limitations to growth. Research describes the regional characteristics of plankton blooms in Florida Bay and on the Florida Shelf west of the Bay, including the dynamics of the ~annual bloom cycle in the Central and West regions. Understanding the causes and dynamics of the apparent sudden onset of intense blooms in the early 1990s remains speculative. It is not possible to choose from among several hypotheses about the cause of this phenomenon based on the results of research so far. Research has not investigated the possible influence of variable grazing rates and/or flushing (or residence time) on bloom occurrence and intensity in Florida Bay.

**Level of synthesis**

<b>Description</b>	<p><b>Trends</b> – Water quality monitoring data documents the timing and general extent of bloom phenomenon over the last 10 years or so. Paleocological data documents possible periods of intense blooms as long ago as the early 1800s.</p> <p><b>Species composition</b> – Research characterizes the different characteristics of blooms in the Central and West regions. Included are results documenting difference among dominant species in terms of nutrient uptake and growth rates.</p>
<b>Correlation</b>	No results reported for correlative studies linking the onset and/or peak concentrations of blooms to water quality characteristics or to variation in driving processes.
<b>Mechanistic models</b>	<p><b>Bloom and plume</b> – quantitative research relates onset of bloom on Florida Shelf to a trigger provided by the input of silica in Shark River flow.</p> <p><b>Central region</b> – results demonstrating the dominance of <i>Synechococcus</i> in the Central region leads to a mechanistic model for this bloom based on some of the unique characteristics of <i>Synechococcus</i>, i.e. high nutrient uptake at low concentrations and variable buoyancy, but this model has not been tested quantitatively.</p> <p><b>Onset, persistence and fate</b> – general mechanistic model that blooms result from an imbalance between growth rate and losses due to grazing and flushing is invoked, but this model has not been used quantitatively to investigate the observed dynamics of blooms in Florida Bay.</p>
<b>Simulation models</b>	Plankton is included as a component of the water quality model by Cerco (2000), but it is not known whether the mechanics of Cerco's model are consistent with either the detailed observations of blooms in Florida Bay and the interpretation of these observations.

**Question 4 - Seagrass Ecology**

*What are the causes and mechanisms for the observed changes in seagrass community of Florida Bay? What is the effect of changing salinity, light and nutrient regimes on these communities?*

**Coverage of topic**

Research has documented the patterns and extent of dieoff associated with the event that began in the late 1980s, recovery of seagrass communities following that event, and the occurrence of several recent, but more limited, occurrences of dieoff. Two complementary conceptual models have been developed to explain the course of the original dieoff event and conditions in the ecosystem leading up to and following the event. Focused research has tested various elements of these models, confirming some (e.g. sulfide stress contributing to primary dieoff) and limiting the role of others (e.g. labyrinthula infection limited by salinity). A seagrass unit (i.e. plot-scale growth and metabolism) model is under development by two groups (Madden and Burd). Results of this research should provide a quantitative test of the conceptual models for dieoff; however these results are not reported as part of the synthesis document. Research has yet to address some plant metabolic and community responses to conditions in the ecosystem, such as sediment characteristics, water temperature, salinity and light levels.

**Level of synthesis**

<b>Description</b>	<p>FHAP surveys of seagrass occurrence and composition.</p> <p>Zieman ongoing monitoring of seagrass growth/productivity at selected field sites.</p> <p>Results of paleoecological studies suggest that seagrass periods of seagrass cover have alternated with periods of no seagrass over the last 100 years or so at several sites studied in the Bay.</p>
<b>Correlation</b>	<p>Fourqurean model correlates community composition with water quality characteristics.</p> <p>Zieman et al 1999 correlate changes in productivity with environmental conditions</p>
<b>Mechanistic models</b>	Unit models under development, but results not provided in synthesis.
<b>Simulation models</b>	Landscape model under development.

**Question 5 - Higher Trophic Levels**

*What is the relationship between environmental and habitat change and the recruitment, growth, and survivorship of animals in Florida Bay?*

**Coverage of topic**

The potential scope of research on higher trophic level species in Florida Bay is almost open ended. To limit the scope in a rational way, research is limited to a set of species for which sufficient survey data exist to begin immediately to answer questions about the influence of environmental conditions in the ecosystem on species abundance and community structure. For a few key species, research provides a fairly complete coverage of issues raised by the central question, e.g. pink shrimp. For other species, the analysis of available research results is still underway.

**Level of synthesis**

<b>Descriptive</b>	In general, the data on higher trophic level species are sparse and usually highly variable. Therefore, simple description of the data holds little potential for progress on the question, and correlative studies are the primary level at which synthesis occurs.
<b>Correlation</b>	A large amount of work on correlative studies for a number of species and communities. Much of this work is summarized in Table 7.1.
<b>Mechanistic Models</b>	Mechanistic models have been investigated for individual growth and survival response to salinity and temperature, sometimes in combination with available habitat. In a few cases, such as shrimp and lobster, these individual-based models have been aggregated to investigate population response to changing conditions in the ecosystem. Mechanisms controlling the recruitment (transport) of larvae into Florida Bay have been investigated.
<b>Simulation Models</b>	In the case of shrimp (and lobster) the aggregated, population-level models have been driven by simple, regression-base models linking Everglades hydrology to salinity in the Bay, and these hybrid models have been used to investigate the sensitivity of the population (i.e. fishery yield) to water management activities.

## ***Progress on modeling***

### **Physical Processes**

Although still not available as a management tool, steady progress has been made toward developing a predictive capability for salinity and circulation changes in Florida Bay and connecting coastal waters as follows:

- 2-D hydrodynamic models with coarse grids have been developed for Florida Bay as pilot projects by J. Wang (finite element) and J. Hamerick (finite difference) that show encouraging salinity pattern results that are similar to observations.
- Better estimates of surface and ground water inflows are available from the recent measurements and hydraulic model results of USGS and SFWMD.
- Improved estimates of evaporation are available from recent studies by R. Price, P. Swart, W. Nuttle, and N. Smith.
- Improved estimates of precipitation patterns and quantities are available from calibrated NEXRAD measurements (P. Willis).
- Measurements of interior basin circulation and exchange processes are available to improve understanding of Bay dynamics, quantify residence times and help validate and improve hydrodynamic models (T. Lee, E. Johns, V. Kourafalou, and N. Smith).
- Modeling Terms of Reference were established by the PST and approved by the PMC.
- A Standard Data Set has been established for model use (J. Pica).
- An interagency nested model program has been formulated using regional hydrodynamic and hydrological models to provide boundary conditions for the Florida Bay model (SFWMD, NOAA, USGS).

### **Water Quality**

The water quality model (Cerco et al. 2000; Fig. 5.14 and 5.15) linked modules including water-column eutrophication, seagrass dynamics, sediment diagenesis, solids and nutrient resuspension, and benthic algal production. To our knowledge, this is a first for Florida Bay. In fact, we know of few systems that presently have a model application to rival the current effort in Florida Bay. The model does require substantial upgrading, however, to fully represent processes in the Bay.

Interpretation of results from the water quality model was severely compromised by lack of a verified hydrodynamic model operable on the same time scale as the water quality model. The major uncertainty in the system nutrient budget is transport across the western boundary and through the Keys passes.

### **Plankton Blooms**

This simulation model will be a component of a water quality model.

### **Seagrass Ecology**

Statistical modeling was commissioned by the Restudy consistent with recommendations from the 1998 Seagrass Modeling Workshop (Fourqurean et al. in press). The goal of this work is to seek relationships between water quality variables and seagrass species composition and

abundance, which if sufficiently strong, can be used to predict the effects of various alterations in Florida Bay salinity regimes. The statistical models developed in this project will be used in conjunction with output from other models to predict the effects of Restudy scenarios on the benthic habitats of Florida Bay. The statistical model will not address mechanisms or degree of change in water quality that result from Restudy scenarios; other models (like the NSM, FATHOM, and the Florida Bay salinity transfer function models currently employed by the Restudy) must simulate water quality changes across Florida Bay that will provide the input to the new models developed in this project. As a consequence, it is anticipated that the benthic habitat change predictions of the statistical models will be the most reliable in the regions most closely coupled with water management practices, i.e. in the enclosed, mangrove-lined estuaries on the fringe of Florida Bay.

In addition, other seagrass modeling efforts have recently been initiated. These include the development of both seagrass unit models for *Thalassia* and *Halodule* and a landscape model that will take output from the unit models.

### **Higher Trophic Level Species**

Two types of models have thus far been applied to HTLs research in Florida Bay. Empirical, statistical models have been used to explore data for patterns that suggest the major processes driving variation in species abundance and community structure. Complementing these models are simulation models, often incorporating population dynamics, to examine the sensitivity of individual organisms to varying characteristics of their habitat, such as bottom cover and salinity. Statistical Models

### **Exploratory General Additive Models**

Johnson et al. (2001, 2002a, 2002b) assembled a database for Florida Bay that integrated six independent forage fish/macro-invertebrate studies conducted between 1974-1997. General additive models were used to determine which major forcing functions and habitat factors control their abundance and distribution. Hindcasts of density distributions across the Bay were made with these models and used to compare density, biomass, and evenness in wet seasons and dry seasons of a representative wet (1995) and dry (1991) year.

### **Forecasts of the Tortugas Shrimp Fishery**

Several empirical statistical models have been used to relate Tortugas catches or catch rates to indices of freshwater inputs to Florida Bay. Browder (1985) found a statistical relationship between quarterly Tortugas catches and the average water level in ENP monitoring well P35. Later Sheridan (1996) developed a statistical model that related annual Tortugas catches to Everglades well and rainfall data, as well as air temperature and Key West sea level, the previous spring and summer. The Sheridan model, which was updated every year with new data, successfully predicted Tortugas catches for the upcoming year for a number of years.

More recently, Browder (2000) developed a statistical model relating annual average Tortugas catch rates to the rainfall of several prior months. A second empirical model was prepared (Browder 2000) to test alternative configurations of the water management system proposed in the "Restudy" that developed the Comprehensive Everglades Restoration Project. This model related Tortugas catch rates of recently recruited shrimp to releases of fresh water into

Everglades National Park at its northern boundary immediately downstream from the leveed Everglades Water Conservation Areas.

### Simulation Models

- A simulation model was developed to predict survival, growth of juvenile pink shrimp cohorts and potential harvests from these cohorts as a function of temperature and salinity in Florida Bay (Browder et al. 1999). The model was recently refined with data from new laboratory experiments (Browder et al. 2002). A spatially explicit individual-based model for Caribbean spiny lobster (*Panulirus argus*) was developed in 1993 (Butler (1994). Reformulations of the same model have been used to investigate a variety of issues, including (1) the potential effect on lobster recruitment of a massive loss of nursery habitat structure due to a sponge die-off (Butler et al. in press), (2) the
- Table 7.1: Summary of forage fish models and significant factors consequences of temporal and spatial variation in post larval supply on recruitment (Butler et al. 2001), (3) the effect of nursery habitat structure and geographic specificity on recruitment (Butler et al. 2001), and (4) the direct and indirect consequences of altered salinity on recruitment (M. Butler, pers. comm.).
- Richards (in prep.) examined the relationships between temperature and salinity and growth rate in crocodiles (*Crocodylus acutus*), by tracking 30 radio-tagged hatchlings in the vicinity of the Turkey Point Power Plant for up to several weeks.
- Substantial progress has been made in the development of a bioenergetically based individual larval spotted seatrout model to simulate metabolic rate, consumption, and growth as a function of temperature and salinity (Wuenschel 2001).
- A spatially explicit prey-predator model for spotted seatrout and pink shrimp coupled to physical processes was developed for Biscayne Bay (Ault et al. 1999; Ault et al. 2003; Wang et al. 2003). The spotted seatrout component of the model was individual-based.

## Focus on Restoration

What role can the Florida Bay Science Program play in the restoration of the Bay and in CERP? What information on the ecosystem will be most useful to resource managers, and what should the Program do to develop this information and deliver it to the resource managers in the cooperating agencies and to the interagency groups established to guide CERP?

Restoration focuses attention on the relationship of Florida Bay to Everglades hydrology and on evaluating the effects of alternative water management practices. The Working Group of the Interagency Task Force identifies three overarching goals that guide ecosystem restoration in South Florida. These are 1) get the water right, 2) restore and enhance the natural system, and 3) transform the built environment (Working Group 1998). The most important goal for restoration of Florida Bay and adjacent marine systems is to get the water right. This means providing freshwater flows with the right quality, quantity, timing and spatial distribution. Determining the “right” quantity, quality, timing, and distribution of freshwater will require specific scientific information. Goals for restoration define the need for scientific information; however the specific information that is needed will change over time as restoration progresses and our understanding of the natural systems increases.



This section compiles information about the restoration of Florida Bay and research needs associated with it. Ecosystem restoration in South Florida will affect Florida Bay in specific ways. These anticipated effects point to areas where research can be particularly helpful setting goals, reducing uncertainties, and documenting restoration progress. The approach of adaptive management, which has been adopted to guide restoration, establishes these roles for research and monitoring as part of a new relationship between resource management and research that is still evolving.

### ***Florida Bay Science Needs***

A committee of the National Research Council (NRC 2002) identified anticipated impacts of Everglades restoration on Florida Bay as part of its examination of the role of the Florida Bay Science Program in relation to CERP. Principal among these impacts are the following: 1) increased freshwater flow reaching Florida Bay from the Everglades, albeit from Shark Slough via a coastal current around Cape Sable rather than through Taylor Slough; 2) increased loading of nitrogen associated with freshwater from the Everglades and leading to more frequent and/or more intense plankton blooms; and 3) resulting perturbation of seagrass communities and decreased water clarity. This committee recommends that a focused technical review should be carried out to evaluate these potential impacts on the Florida Bay ecosystem more fully.

In order to support such a review and evaluation, the NRC committee (NRC 2002) identifies the following areas of needed research:

- better information on components of the water budget for the Bay, in particular on groundwater discharge and surface water runoff;
- information on the effects on nitrogen and phosphorous fluxes to the Bay of anticipated changes in the distribution and amount of freshwater runoff in the Taylor Slough/Craighead basin and in Shark Slough;
- better understanding of nutrient loads contributed from different sources and of the bioavailability of these nutrients;
- historical characterization of the Bay's water quality drawing on a variety of information sources, such as anecdotal accounts;
- development and application of a hydrodynamic circulation model and a water quality model for the Bay;
- application of statistical, time-series and "box model" mass balance calculations to estimate the influence of CERP projects on Florida Bay;
- better definition of the potential effects on the ecosystem of "distant drivers" that are unrelated to, and largely beyond the influence of, CERP activities; these include phenomenon such as hurricanes, sea level rise, population growth, economic activities, etc.

Finally, the NRC (2002) report recommends that cooperating agencies adopt a more formal approach to managing ecosystem research and integrating the research with resource management. In particular, the committee calls on agencies to execute a formal agreement that identifies one modeling approach, from among several potential approaches, that will function as the interface between the regional hydrology model that supports restoration and water resource planning in South Florida and a hydrodynamic model in Florida Bay.

## ***Science in Ecosystem Restoration***

Stepping back from these specific research needs, another NRC committee (NRC 2003) has reviewed the different ways in which scientific information contributes to ecosystem restoration. This report is the result of the Critical Ecosystem Studies Initiative, conducted in South Florida by the Department of Interior, but it draws on experience elsewhere in the United States (e.g. the Grand Canyon) for information on the broader role of research and monitoring in ecosystem restoration. Science contributes to defining restoration goals, conceptualizing (i.e. modeling) the ecosystem, and as a tool for institutional learning and the integration of new knowledge into ongoing restoration efforts. This report also discusses some of the challenges that arise from the conflict between objectives for research on one hand and on the other decision-making related to water system design and management.

Science has already made significant contributions to restoration decision-making in South Florida. Integrative environmental science has injected essential new information, for example about water quality requirements to maintain the Everglades ecosystem, into the relatively staid, conservative practice of water management that prevailed just a few years ago. Scientific information from monitoring that documents the conditions and trends in the region's ecosystems have been persuasive at key junctures in motivating a response to emerging problems and in decisions on how to address these problems. In addition, the widely used device of peer-review has been adopted to support management decision making by assuring the quality of available information and analytical tools. The present structure of the Florida Bay Science program reflects an appreciation of these contributions and the intent to secure similar benefits for the management of Florida Bay and adjacent marine systems.

The NRC (2003) report on the CESI program and a contemporaneous report by GAO (2003) on science coordination in South Florida both make recommendations on how to improve the management of research for restoration and the application of the results of research and monitoring to resource management activities, including CERP. These recommendations call for more centralized and independent management of the combined interagency science effort in the region. Both view RECOVER, the coordinating body for research and monitoring within CERP, as one component in a more comprehensive restoration and natural resources science program. In light of these recommendations, it is unclear what will be the future for the Florida Bay Science Program as a distinct interagency effort. However, in the meantime as this future unfolds the information contained in these recent reports (NRC 2002, 2003 and GAO 2003) can be used to help focus the interagency research in Florida Bay on topics that are most relevant to ecosystem restoration in South Florida.

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## Appendix: Unresolved Issues/Ongoing Research

The following is a synopsis of information on unresolved issues and ongoing research from the chapters dedicated to each central question.

### ***Physical Processes***

#### **Winds and Storms**

A number of questions remain: What are the long-term effects of the daily development of convergent wind patterns over the Bay? What are the magnitudes and spatial and temporal scales of this mesoscale wind forcing? How does it influence the south Florida seascape in terms of water levels, evaporation and precipitation patterns, circulation and exchange between water bodies, and surface and groundwater inflows to the Bay? What is the effect of winds on residence times of the interior waters of the Bay? It is not clear what changes may occur from intense cyclones, nor how long these changes may persist. Predictive modeling of different classes of tropical cyclones is needed to anticipate these impacts.

#### **Precipitation**

Do the spatial patterns of Bay surface salinities measurably change as a result of the heterogeneity of precipitation? To what degree has precipitation over the Bay been changing because of land use changes on the peninsula?

#### **Evaporation**

What is the mean rate of evaporation in Florida Bay? What is the spatial and temporal variation of evaporation? How reliable are long-term estimates of evaporation? How much additional precision can be gained by refinement of stable isotope methods? Other questions regarding evaporation include: To what degree does the seasonality of evaporation need to be considered in evaluating the effect upon salinity patterns of different water management scenarios? What is the effect of the Bay's bank and basin topography upon evaporation? The rate of evaporation over the extensive, shallow banks may be different from the average estimates used to date.

#### **Surface water inputs**

Simulation models under construction by the United States Geological Survey (USGS) and the SFWMD in conjunction with their ongoing measurement programs are expected to resolve any remaining uncertainty concerning surface water discharges into Florida Bay.

#### **Groundwater inputs**

Clearly many unresolved questions remain concerning not only the absolute amount of groundwater input to Florida Bay but also its temporal and spatial variability and the resulting salt and nutrient flux. The consensus at present is that the water quality implications of groundwater input from either the southern Everglades or Florida Keys may be more significant than its physical consequence unless the larger estimates prove to be correct.

#### **Sea level and Tides**

No major unresolved issues remain concerning tides. Studies are underway concerning the effects of sea level differences on inter-basin exchange and upon flow through the passages between the Florida Keys. It is also not clear how long-term sea level differences between the

Gulf and Atlantic affect the observed mean southeastward flow that transports water to the Florida Keys reef tract.

The depth over many of the banks is approximately equal to or less than the range of seasonal fluctuations in mean sea level. What consequences might this have for rates and patterns of inter-basin water exchange in the interior portion of the Bay? What are the rates and pathways of exchange between the interior basins and across the banks in the western, central, and eastern regions of Florida Bay and with the southwest Florida shelf?

### **Salinity**

Although the spatial and temporal variability of salinity in Florida Bay is well documented and continues to be monitored both with field surveys and fixed instruments, a number of unresolved questions remain, such as: How is the salinity of Florida Bay influenced by atmospheric forcing on time scales from daily to inter-decadal, including significant transient meteorological events such as hurricanes and tropical storms? How do the spatial patterns of evaporation, precipitation and basin residence time affect Bay salinity distributions? For example, does hypersalinity occur where it does because evaporation is greater over broad shallow banks than in the rest of the Bay, or because exchange with lower salinity water is restricted? How do the salinity records inferred from paleoecological data compare with salinity values measured over the past 45 years? Is there a statistical transfer function sufficient to adequately describe the effect of fresh water flows on salinity for the purposes of predicting the effect of restoration scenarios upon Bay salinity? If so, over what spatial domain does it apply?

### **Circulation**

A better understanding of flow across banks, and bank characteristics in general (e.g. cover, elevation, salinity, and temperature), will be necessary for successful hydrodynamic and ecological modeling of the Bay interior.

It is essential to better describe and understand the net southward flow that couples the eastern Gulf and Atlantic coastal region of the Keys in order to aid future model development and facilitate informed management decisions. What is the influence of the Loop Current or synoptic winds over the west Florida shelf on driving this flow? Are topographic constraints on the southwest Florida shelf important? How is the flow related to observed southward flows farther north on the west Florida shelf that appear to diverge away from the coast before reaching the southwest shelf (Yang et al., 1999)?

### **Exchanges with Adjacent Waters**

There is evidence from the large-scale hydrographic surveys that at times these high salinity waters can form a near-bottom salty layer in the Hawk Channel region. However, very little is known about this process. How are the salty bottom layers formed? What are their spatial extent and transport pathways? What are their durations?

Transports across the western boundary are very uncertain at this time; however, field research is planned to improve understanding of transport processes and help quantify this exchange. Can the bank "overtopping" process explain the observed net outflow from the central part of the Bay.

More effort is needed to quantify and monitor Mean Gulf to Atlantic flows through western Florida Bay to the Keys coastal zone to better understand the physical processes involved. Is it related to the position and configuration of the Loop Current as Gulf models and satellite observations suggest? Coupling of a large-scale model that includes the Gulf and Straits of Florida to a finer scale Florida Bay model is needed to address this issue.

## **Water Quality**

We need to accurately predict the sensitivity of the Bay's nutrient cycles to changing fresh water flow to the Bay, and the resultant change in the Bay's salinity regime. For much of the Bay, any factor that increases P availability either by increasing sources or decreasing removal is likely to exacerbate the current problems of the Bay. We also need thorough understanding of the Bay's nutrient cycles, particularly with regard to the fate and effects of dissolved organic nitrogen inputs from the Everglades. Questions that the future program should address in order to meet these needs are as follows.

1. What are the sources of nutrients that sustain algal blooms?
2. How will changing fresh water flow directly and indirectly alter the supply and availability of nutrients in the Bay? What effect does changing salinity have on nutrient availability in the Bay?
  - How will the quality and quantity of nutrient outputs from the Everglades change with restoration?
  - What is the fate and effect of dissolved organic matter from the Everglades and how will this change with restoration?
  - What effect does changing salinity have on nutrient cycling and availability in the Bay?
3. What effect does a change in seagrass community structure have on nutrient availability in the Bay? Has seagrass mortality only increased nutrient availability by releasing nutrients from this detrital source, or has seagrass mortality also caused other less direct changes, such as a decrease in the capacity of the sediments to sequester nutrients?
4. How do we deal with the spatial heterogeneity of internal nutrient cycling in the Bay?
5. What is the quantitative role of microphytobenthos in nutrient cycling and how is this likely to change with Everglades restoration?
6. To what extent is atmospheric deposition of nutrients contributing to ecological changes in Florida Bay? What is temporal variability (including long-term trend) of this nutrient source?
7. Is ground water an important nutrient source in Florida Bay? If so, what is the spatial and temporal pattern of this input?

## Summary of Ongoing Research

1. Continued monitoring of ambient water quality in Florida Bay
2. Continued monitoring of freshwater inflows and loads with expansion of network along Florida Bay and southwest Florida/Gulf coast beginning
3. Continued monitoring of coastal circulation and biological and chemical parameters, with interpretation of transport and exchange of South Florida coastal waters
4. Expanded research into nutrient cycling in wetland/mangrove areas and seagrasses/epiphytes
5. Study of carbonate system - P - Fe relations
6. Characterization of chemical structure of organic C and N from wetland/mangrove areas
7. Assessment of microbial bioavailability of organic C and N from wetland/mangrove areas
8. Expanded measurements of benthic nitrogen fixation, nitrification, and denitrification rates
9. Measurements of phytoplankton N uptake rates
10. Quantification of microbial loop parameters: heterotrophic bacterial numbers, bacterial production, nanoflagellate/protist grazing rates, and phytoplankton primary production
11. Effects on the coastal Everglades ecosystem of variability in regional climate, freshwater inputs, disturbance, and perturbations
12. Development of N and P mass balance models and measurements of nutrient cycling rates in Florida Bay
13. Assessment and monitoring of dissolved N in Florida Bay
14. Measurement of nutrient fluxes through Florida Keys passes
15. Monitoring of salinity and estimates of fluxes of water, TN, and TP across the southern Everglades mangrove zone
16. Development of an integrated hydrodynamic and water quality model to evaluate relationships with freshwater flow and oceanic/Gulf hydrodynamics and exchange is in a planning phase

## Plankton Blooms

(No information provided in synthesis chapter.)

## Seagrass Ecology

### Field Assessment

- FHAP is continuing spring and fall sampling and has incorporated (since spring 2001) measurements of photosynthetic characteristics of *Thalassia* using PAM-fluorometry at each station, in addition to the Braun-Blanquet and standing crop measurements.
- FMRI (Carlson) is continuously monitoring benthic light availability at fixed stations in several basins
- Zieman is maintaining the long-term productivity measurements

### Experimental

- SFWMD is funding a new study entitled “High salinity, nutrient and multiple stressor effects on seagrass communities of NE Florida Bay” (Koch and Durako). The results of this study are intended to help parameterize the unit model with data from Florida Bay seagrasses.

- FMRI (Carlson) bucket experiments have been conducted to examine effects of multiple stressors (sulfide nitrogen and light) on seagrasses in situ.

## ***Higher Trophic Level Species***

### **Unresolved Issues/Research Needs**

Criteria used to propose future research topics were as follows: 1) follow-up of promising recent research expected to sharpen or broaden answers to Question 5; 2) addressing promising new hypotheses that replace failed hypotheses; 3) development of performance measures based on species and communities most likely to be affected by CERP changes; and 4) addressing gaps in the current program where new information suggests higher priority should be assigned. The following series of topic areas fit one or more of these criteria.

*Location of Nursery Areas of Major Game Fish Species* - Many sought-after gamefish species are found in Florida Bay as pre-adults and adults, but the current nursery grounds of most their populations are not delineated. This includes red drum, snook, tarpon, bonefish, and gray snapper. These nursery areas need to be delineated so that the potential effect of water management changes on salinity patterns, nutrient inputs, and other conditions in these areas can be predicted.

*Influence of Habitat and Environmental Variables on Species Composition and Trophic Dynamics* - The following non-mutually exclusive hypotheses about factors influencing the abundance and relative abundance of water column and seagrass canopy species should be explored.

Hypothesis 1: Density and abundance of bay anchovy is related to salinity fronts.

Hypothesis 2: Density and abundance of canopy species is related to seagrass diversity.

The database assembled by Johnson et al. (2001) provides the opportunity to develop trophic network models for Florida Bay. Separate network models should be prepared for the Bay's sub regions because of the major differences in the food web base among sub regions suggested by Chanton et al. (2001), Evans and Crumley (in review) (see also Evans et al. [2001]), and Butler et al. (2001). Analysis and comparison of trophic structure in the various regions of the Bay could be used to organize information about higher trophic level species and assess affects of salinity changes resulting from changes in water management.

### *Factors Affecting Postlarval Immigration:*

- Immigration into the Bay's Interior - To what extent and how much of the interior of the Bay is accessible to offshore-spawned species? What factors cause the accessibility of the inner bay to vary? This information would allow determination of potential benefits of improved conditions to these species. Greater coordination of biological and physical research on the movement of water and early life stages into the Bay's interior is needed. Physical research in the interior of the Bay was initiated last year, opening new opportunities for collaboration.
- Immigration to Florida Bay - Recent research suggests that the major pathway for transport of pink shrimp postlarvae from the Tortugas to Florida Bay may be across the southwest Florida shelf. Research on larval immigration to Florida Bay nursery grounds



from the west is hampered by a lack of physical oceanographic work that addresses questions biological researchers need to know.

- **Effect of Larval Behavior and Freshwater Inflow on Larval Immigration Rates** - Does the volume and timing of freshwater inflow influence that magnitude of influx of postlarvae to Florida Bay? Freshwater inflow may provide directional cues or otherwise influence the rate of larval immigration from offshore spawning grounds to nearshore nursery grounds.

*Effect of Salinity on Survival and Growth* - Integrated studies that might include models, supporting field studies, laboratory experiments, and statistical analyses should be conducted to quantify relationships of survival, growth, and other processes to salinity. This includes continued development and application of lobster, shrimp, gray snapper, and spotted seatrout models.

*Quantification of Size-Related Predation Mortality* - Better quantification of size-related predation mortality is needed to adequately address the effect of salinity on survival through the effect of salinity on growth. This issue is especially pertinent to pink shrimp, spotted seatrout, gray snapper, and lobster. Results are needed to refine and quantify simulation models.

*Effect of Water Quality on Survival and Growth* - This question has not been specifically addressed in current research in Florida Bay. Effects of both nutrient enrichment and common chemical contaminants on Florida Bay fish and macroinvertebrates may be relevant to determining effects of changes in water management.

*Effects of Benthic Habitat on Settlement, Survival, and Growth* - What characteristics of habitat lead to initial settlement? How do characteristics of settlement habitat affect survival and growth? How faithful are animals to the location of first settlement? What causes movement and where do animals go? Information on these questions is needed to further refine simulation models.

*Identification of Other South Florida Coastal Areas with Enhanced Mercury Bioaccumulation in Fish* - The sensitivity of fish from the mangrove ecotone of the entire Ten-Thousand Islands complex of southwest Florida suggests the need for a monitoring program to establish mercury concentrations in susceptible fish species and a research effort to determine the mercury sources and responses to future CERP changes in the volume and timing of freshwater flows.

## **Ongoing Research**

*Modeling pink shrimp recruitment from Florida Bay* - This project continues development of a simulation model and associated performance measure to evaluate the potential impact on Florida Bay of upstream water management changes resulting from efforts to restore the Greater Everglades ecosystem.

*Regional Assessment of Sponge Dynamics and Sponge Fishery Impacts* - This project is part of a multi-year investigation of the hard-bottom communities of Florida Bay and the Florida Keys. It combines modeling, laboratory, and fieldwork to explore the relationship of spiny lobster

population dynamics to spatio-temporal patterns in the structure of bottom habitat and environmental variables.

*Population Studies, Abundance, Habitat Use, Trophic Descriptions, and Reproductive Status of Marine Turtles Inhabiting Florida Bay* - Purposes of this study are to 1) capture and tag sea turtles in Florida Bay to continue long-term monitoring of individual growth rates, foraging-site fidelity, residency rates, health status, and trends in abundance; 2) elucidate the trophic role of loggerheads as apex predators in Florida Bay; 3) provide detailed descriptions of loggerhead habitat use and behavior; and 4) examine the sexual maturity and reproductive frequency of adult-sized loggerheads inhabiting Florida Bay. The principal study area is the central-western region.

*Reef Fish Community Dynamics and Linkages with Florida Bay* - This continuing project will apply a visual sampling strategy to quantify coral reef fish community changes.

*Development of Spatially-Explicit Models to Predict Growth-Potential of Age-0 Gray Snapper, Lutjanus griseus, in Florida Bay during Restoration of Freshwater Flows* - The general goal is to examine patterns of growth in juvenile gray snapper and develop a bioenergetic model of growth that is a function of temperature, salinity, and fish size. This model will be extended into a spatially explicit calculation of potential fish growth using historical environmental data as well as predicted changes in the environment of Florida Bay under different water management strategies.

*Upstream Larval Supply to Florida Bay—the Dry Tortugas Connection* - This project explores the pathways and enabling transport processes for migration of larval fish, shrimp, and lobster from the Dry Tortugas to Florida Bay. Emphasis is on the role of episodic, mesoscale events, such as those involving eddies and the Tortugas gyre.

*Atlas of Life Histories of Juvenile and Small Resident Species in Florida Bay* - The Atlas will include information on the range, reproduction, diet, spatial and temporal abundance and distribution, and length-frequency distributions in the Bay.

*ATLSS Model of Coastal Wetland Fishes* - A spatially-explicit model of the resident fishes of the coastal wetlands is being developed by Cline et al. (2001) to further explore the relationships determined by Lorenz (2001a, 2001b).